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Source: Journal of Coastal Research, 36(sp1) : 139-147

Published By: Coastal Education and Research Foundation

URL: https://doi.org/10.2112/1551-5036-36.sp1.139

Journal of Coastal Research	SI 36	139-147	(ICS 2002 Proceedings)	Northern Ireland	ISSN 0749-0208

Sedimentation Processes on Intertidal Areas of the Lagoon of Venice: Identification of Exceptional Flood Events (*Acqua Alta*) Using Radionuclides

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ABSTRACT

Particular atmospheric conditions produce frequent storm surges in the Lagoon of Venice, locally called *"acqua alta"*: the highest event of this kind was registered in 1966. The process became of some importance in the last 100 years, when man-made subsidence caused a gradual sinking of the town and lagoon's bed.

Four cores were collected in a range of intertidal environments of the Northern lagoon to undertake radionuclide studies using profiles of natural ^{210}Pb (using the Constant Rate of Supply and Constant Initial Concentration models) and anthropogenic ^{137}Cs. The best agreement between the three dating methods was found at *San Giacomo*, an eroding saltmarsh at the edge of a navigation channel, with a sedimentation rate ranging from 0.22 to 0.29 cm yr^{-1}. This site recorded the flood of 1966 as a characteristic break in the $^{210}Pb_{ex}$ profile, as dated by the CRS model. For the Cona tidal flat, both the CRS model and the position of the Cs peak-marker gave similar accretion rates, 0.16 and 0.18 cm yr^{-1}. However, two different CIC accumulation rates were calculated, 0.29 cm yr^{-1} for the deepest section of the core and 0.17 cm yr^{-1} for the uppermost part. The break in the 210Pbex profile, again corresponds to the flood of 1966. The effects of subsidence were recorded as an increase in accumulation rate between 1910 and 1931, when there were up to 15 floods per year (1926). Higher sedimentation took place during the period 1958-1973, when years with over than 50 flood events were frequent. The maximum deposition rate (0.43 cm yr^{-1}) occurred again around 1967, consistent with the record of the exceptional flood, if the accuracy of the dating is taken into account. The sedimentation rates calculated for the two other mudflats, *Rosa and Saline,* were more problematic to interpret because of downcore mixing and/or the occurrence of reducing conditions.

ADDITIONALINDEXWORDS: *Sedimentation rates, radionuclides, floods, intertidal areas*

INTRODUCTION

Intertidal areas in recent years have become the subject of intensive investigations, because of their important role in mitigating wave action (BRAMPTON, 1992). In the present context of Sea-Level Rise, recently quantified by the IPCC Panel (IPCC, 2001) in the order of 0.88 m by the year 2100 (worst-case scenario), the role of saltmarshes and tidal flats is of primary importance, as they can act as "dynamic" coastal defences. Clearly their capacity of migration is controlled by two factors: first of all the absence of non-natural boundaries (e.g. sea-walls, sea-dykes) which could "squeeze" them; secondly, the availability of sediment to allow vertical accretion.

Sedimentation rates can be studies at several temporal scales, ranging from days, using sediment traps (DAY *et al*., 1998a and 1998b), to months surveying elevation changes with topographic methods (PETHICK, 1992), or Sediment Erosion Tables (DAY *et al*., 1998a and 1998b), to years employing radioisotopes or geochemical horizons (BATTISTON*et al.*, 1988; BONNETT*et al.*, 1988; ALLEN *et al*., 1993; CIAVOLAand COVELLI, 1994; CUNDY and CROUDACE, 1995a; 1995b; ANDERSEN *et al*., 2000). Mature salt marshes or subtidal marine sediments tend to give more consistent dating results than intertidal sites. Bioturbation and physical reworking of particles are meant to be negligible in salt marshes, although some studies from the Solent (U.K.) have shown evidence of mobilisation of Pb and ^{210}Pb (ALLEN *et al*., 1993; CUNDY and CROUDACE, 1995a). On the other hand, dating of salt marshes can also present problems of interpretation arising from the likelihood of discontinuities in accumulation, especially in upper marsh sites or in exposed unvegetated areas.

STUDY SITE AND AIMS OF THE RESEARCH

The lagoon of Venice is the largest lagoon in the Mediterranean and is located in the northern part of the Adriatic Sea (Figure 1). The lagoon has a drainage basin of 1850 km^2 which provides a mean yearly freshwater input of 35.5 m^3s^{-1} (ZULIANI *et al*., 2001), of which the main contributors are Silone River (23.1%), the Dese River (21.1%), the Naviglio-Brenta (14.3 %) and the Taglio-Nuovissimo (13.2%) partially channelised systems.

It has an extension of 550 km^2 and a microtidal regime (average range at Spring Tides in the order of 0.8 m). Particular atmospheric conditions like strong southerly winds (*Scirocco*) and low atmospheric pressures produce frequent storm surges, which can increase the maximum tidal range (PIRAZZOLI, 1991; CANESTRELLI *et al*., 2001). These *Scirocco* winds typically have maximum speeds in the order of 50-60 km h^{-1}, they generally occur in spring and autumn, producing extensive flooding of the historical city centre (PIRAZZOLI, 1991).

A range of man-made changes has affected the lagoon over the period spanning from the 15th to the 19th century. GATTO and CARBOGNIN (1981) present a succinct summary of these anthropogenic activities that included diverting river outflows outside the lagoon, opening and widening the tidal inlets, the creation of water ways for navigation towards the inner coastal area. The last century experienced a boom of commercial activities in the lagoon, leading to exploitation of ground water resources that generated high subsidence rates (GATTO and CARBOGNIN, 1981; CARBOGNIN and TARONI, 1996). The last factor caused a Relative Sea Level Rise, calculated for the period 1930-1970, vary between 3.8 mm yr^{-1} (CARBOGNIN and TARONI, 1996) and 6 mm yr^{-1} (SESTINI, 1992, BONDESAN *et al*., 1995). Following the end of groundwater withdrawal in the early 1970s, land subsidence slowed down, to the extent that it is no longer a problem and some areas have even experienced a rebound (CARBOGNIN and TOSI, 1995; CARBOGNIN and TARONI, 1996).

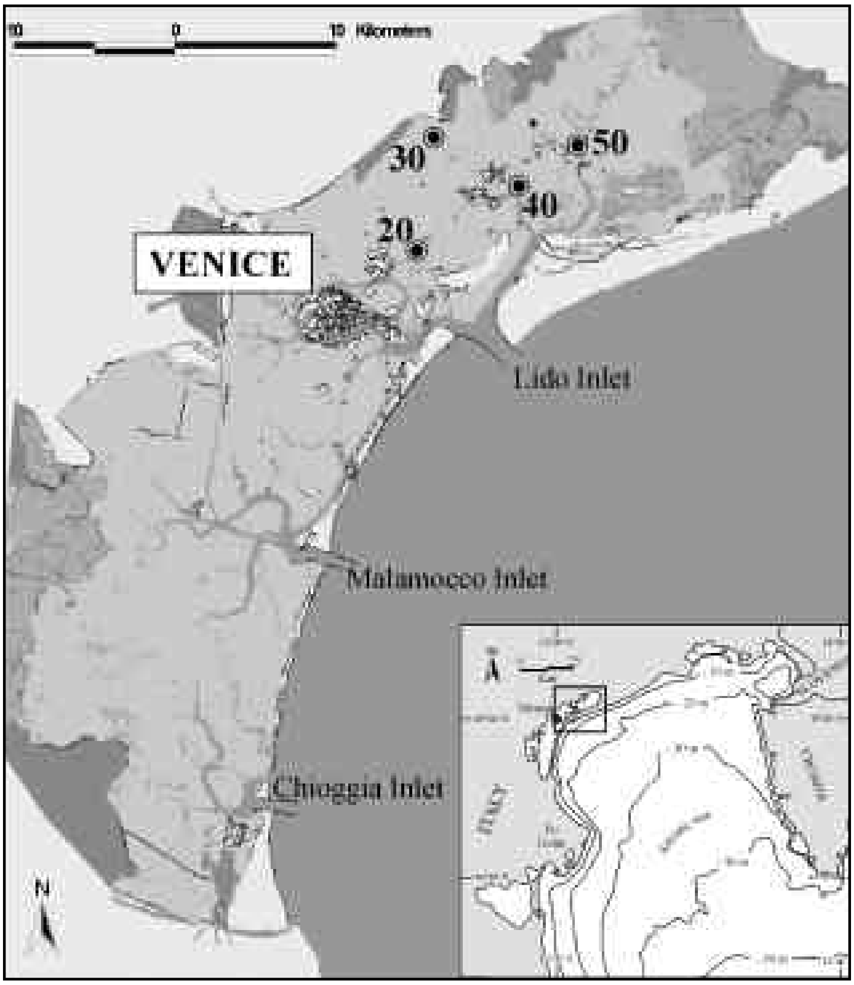

Figure 1. Index map with the location of the sampled sites.

In the central part of the lagoon, the subsidence lead to a progressive drowning of tidal flats and marshes at the side of canals, with a deepening of areas that once became exposed at Low Spring Tides (*velme*), generating vast flat shoals with an average water depth in the order of 1 m below Mean Sea Level (MSL). Secondary effects on the morphology of the lagoon bed were the disappearance of tributary channels branching away from the main ones and a progressive deepening of the main canals, together with a scouring of the bed in the inner part of tidal inlets.

Feed-back processes between estuarine circulation, transport of sediments and phytobenthos were the subject of the Project F-ECTS (EU-MAST III Programme) that supported collection of four push cores, in August 1998, on the salt marshes and mud flats of the northern basin of the lagoon. Radionuclide measurements were undertaken to establish the down-core profile variations of excess-^{210}Pb and ^{137}Cs to obtain the sediment accumulation history over the past century.

METHODS

Sampling method and sedimentological analyses

The cores were collect using PVC tubes, ranging from 9.5 to 10.4 cm in diameter, with lengths between 50 and 100 cm. The cores were opened in the laboratory immediately after collection and subsampled every centimetre for radionculide analyses. As a preliminary description of the cores was made straight after their opening, only selected sub-samples, representative of discrete sedimentary units, were taken for determinations of moisture content, organic matter (% LOI), and grain-size distribution. Determination of moisture content was performed on a wet subsample (2-10 g) which were placed in an oven to dry for 24 hours at 105°C. Organic matter content was determined as Loss On Ignition (LOI) using 3 grams of dried sample that were put in a furnace for 16 hours at 375°C (±5°C). After removing organic matter with H^2O^2, the sand fraction (62.5µm <d< 2 mm) was introduced into a vertical settling tower similar to that of SENGUPTA and VEENSTRA(1968), while the mud (d<62.5 µm) was finally analysed using a Micromeritics Sedigraph, on standard processing resolution. The complete grain-size distributions and statistical parameters were based on the graphical method of FOLK and WARD (1957).

Radionuclides

All the analyses were carried out at the Radiation Physics Research Laboratory of Department of Experimental Physics of the National University of Ireland (Dublin). Further details on the laboratory procedures can be found in MCMAHON (2000). The sub-samples were dried in the laboratory at ca. 90°C, ground to a powder and homogenised with a mortar and a pestle. The absolute water content and the dry bulk density were calculated from the samples after drying, while the porosity was calculated using the formula of RAVICHANDRAN *et al*. (1995). The sediments were analysed for ^{210}Pb and ^{137}Cs by γ spectrometry, from the gamma emission at 46.52 and 661.66 keV, respectively. Three detectors were used in this study, all of them supplied by EG&G Ortec™, one a low energy photon spectrometer (LO-AX or LEPS), and two high-resolution, low-background _ detectors (high purity n-type germanium detectors LB-GMX). The efficiency calibration was directly performed using a standard solution (SRM-4276, supplied by the *U.S. National Institute for Standards and Technology*) containing ^{125}Sb+^{125}mTe, ^{154}Eu and ^{155}Eu, thus providing 13 calibration peaks between 27 and 1596 keV. A separate mono-energetic ^{210}Pb standard (RBZ24, supplied by *Amersham International plc*) was used to calibrate at 46.52 keV. Counting times were typically *ca*. 48 hours, no correction was made for salt content in the sediments.

RESULTS AND DISCUSSION

Sedimentary environments, dating and sediment accretion rates

The determination of recent sedimentation rates is based on two fundamental assumptions underlying ^{210}Pbex accumulation: (1) the "constant initial concentration" (CIC) model, which assumes that the initial $^{210}Pb_{ex}$ concentration in the deposited sediment is always the same, regardless of changes in the sediment accumulation rate; (2) the "constant rate of supply" (CRS) model, which assumes that the supply of $^{210}Pb_{ex}$ to the accreting material is constant when averaged over a timescale of 100-200 years (APPLEBYand OLDFIELD, 1978). In the case of sediment of unvarying composition deposited at a constant rate, the CRS and CIC models are equivalent. The ^{137}Cs method is fundamentally different from the ^{210}Pb method in that it provides date "markers". The depth at which the maximum peak activity is observed can be used to estimate the depth of the 1963 and 1986 horizons, while the depth at which significant ^{137}Cs activities are first recorded can be used to estimate the position of the surface in the mid-1950s (WALLING and HE, 1997). While the ^{210}Pb dating method gives an average accumulation rate for the past 100-200 years, ^{137}Cs is only applicable for the period beginning from 1954 until present.

Palude di Cona (Cona 30)

This core was collected on a tidal flat colonised by Zostera noltii, with the surface sediments covered by a microalgal mat. Grain-size analyses indicate a poorly sorted population with a net predominance of the silt fraction (5 to 8 phi) throughout the core, with a very fine sand component

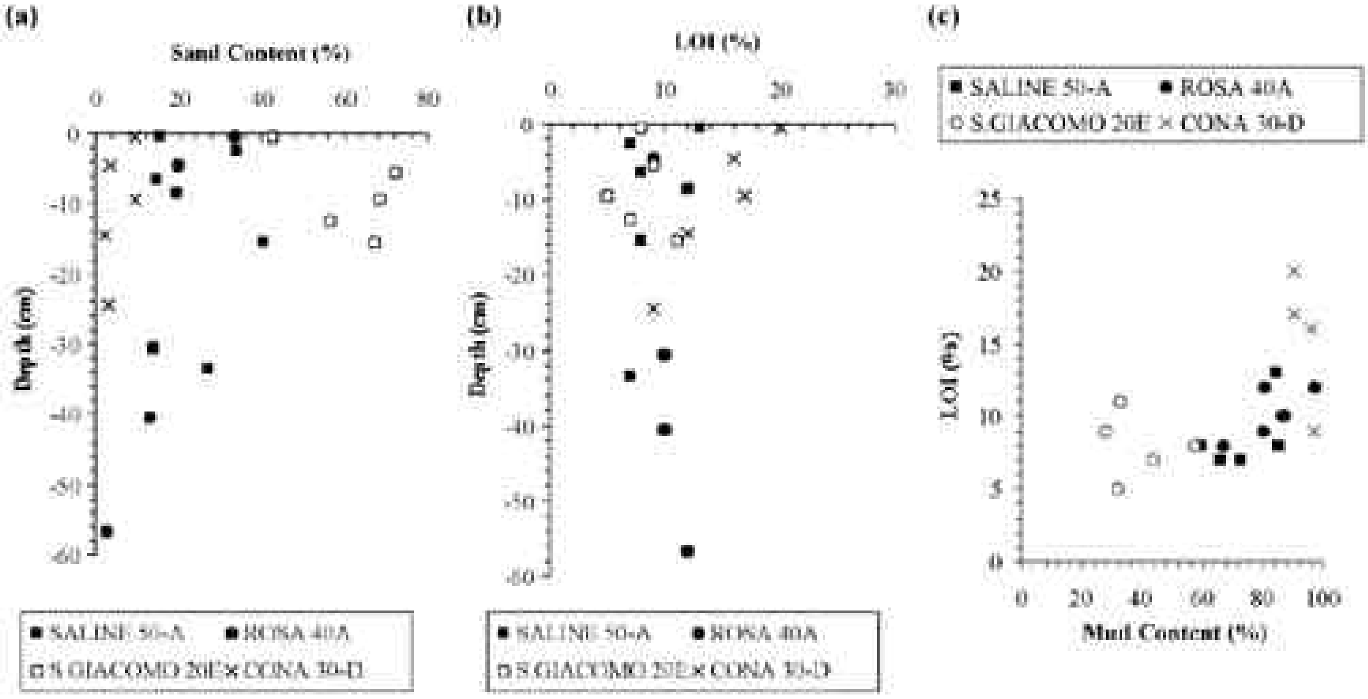

Figure 2. Results of sedimentological analyses: (a) Sand content; (b) Loss On Ignition; (c) Mud content vs LOI.

(3.5-4 phi) decreasing from the top (10%) to the base of the core (3%). Besides having the highest mud content of all the studied cores, the site is also characterised by the highest content in organic matter (20% at the core top, see Figure 2a). Plant debris (roots) was observed down to a depth of 15 cm, especially in the first three centimetres of the core.

The average ^{210}Pb and ^{226}Ra activities from 0 to 23 cm depth are respectively 55.13 (± 7.68) and 29.80 (± 5.02) Bq kg^{-1}. The depth distribution of the ^{210}Pb and $^{210}Pb_{ex}$ activities increase from the sediment interface down to 3 cm depth, and this could account for variations in the sediment composition or sediment grain-size, as the ^{40}K activities also increase in the same depth-interval. The equilibrium between ^{226}Ra and ^{210}Pb is reached below 17 cm depth, indicating that all the $^{210}Pb_{ex}$ has decayed. On the other hand, there was no measurable 137Cs below 17 cm depth. The total inventories indicate 60% of the mean atmospheric $^{210}Pb_{ex}$ flux, while 78% of the expected ^{137}Cs atmospheric input is found at the site (Table 1).

A first interpretation of the $^{210}Pb_{ex}$ profile using the CIC model on the Cona core leads to two different accumulation rates, 0.17 cm yr^{-1} from 2.5 to 4.5 cm depth and 0.29 cm yr^{-1} from 7.5 to 16.5 cm depth, respectively. A second interpretation of the same profile is obtained by best fitting a line between 2.5 and 16.5 cm depth and gives a CIC accretion rate of 0.29 cm yr^{-1}. This assuming that the depth-interval (4.5-7.5 cm) is an instantaneous depositional event. The depth distribution of ^{137}Cs identifies a distinctive peak at 6.5 cm depth, which was assumed it to be the 1963 maximum fallout horizon giving an average sedimentation rate of 0.18 cm yr^{-1}. Based on the CRS chronology, the date of the ^{137}Cs peak was found to be 1968 (± 9), which is coincident with the period of greatest nuclear testing. Unexpected detectable ^{137}Cs levels were found in pre-1950s depths, may be following diffusion or mixing, which could have smoothened the original ^{137}Cs profile, broadening the 1963 peak. CRS accretion rates for this core range from 0.04 to 0.43 cm yr^{-1} (Table 1), with a mean value of 0.16 cm yr^{-1}. This is in good agreement with the accretion rate calculated using the 1963-peak marker of ^{137}Cs (0.18 cm yr^{-1}).

Palude di San Giacomo (San Giacomo 20)

The core was collected on a saltmarsh colonised by *Salicornia sp*. The dominant grain-size throughout the core is 4 phi (fine sand-coarse silt boundary), indicative of a more energetic environment compared with the previous site. This is likely to be due to the location at the edge of a small island near S. Giacomo in Palude, in-between two important navigation channels and thus continuously under the influence of boat waves. Vegetal debris and roots were observed between 7 and 12 cm depth, especially in the first three centimetres.

Table 1. Summary of results from the radionuclide analyses.

Parameter	Method	CONA	SAN GIACOMO	ROSA	SALINE
$^{210}Pb_{ex}$ Total Inventory (Bq m^{-2})		2693 ± 229	932 ± 241	1427 ± 310	2365 ± 580
Average $^{210}Pb_{ex}$ (Bq kg^{-1})		29.90 ± 9.30	8.67 ± 8.20	9.79 ± 10.30	13.89 ± 14.08
^{137}Cs (Bq kg^{-1})		2.80 - 67.92	2.48 - 41.63	2.20 - 19.25	4.94 - 16.91
Depth of Appearance (cm)	$^{210}Pb_{ex}$	16 - 17	24 - 25	43 - 44	25-26
	^{137}Cs	16 - 17	24 - 25	43 - 44	unreached
Sedimentation Rate (cm yr^{-1})	CRS/ Mean	0.04-0.43 / 0.16	0.03-0.47 / 0.22	0.04-2.06 / 1.39	0.03-2.66 / 0.53
	CIC Method	0.29 (0.17 ?)	0.25 (0.53 ?)	1.32	0.98
	^{137}Cs 1963-peak	0.18	0.29	0.47 ?	0.27 or 0.41 ?

The average ^{210}Pb and ^{226}Ra activities calculated from 0 to 25 cm depth in this core are respectively 36.28 (± 6.49) and 27.62 (± 4.92) Bq kg^{-1}.. On the $^{210}Pb_{ex}$ depth-profile, the activities increase from the interface to a depth between 6-7 cm (surface mixed layer?), before decreasing more or less logarithmically. As there was no detectable ^{137}Cs below 25 cm, the first value was used in the CRS model for deposition dates calculation. It leads to an annual $^{210}Pb_{ex}$ deposition rate that represents only 21% of the expected mean $^{210}Pb_{ex}$ atmospheric flux over the northern hemisphere landmasses (Table1). The ^{137}Cs, as for $^{210}Pb_{ex}$, exhibited a pronounced deficit, with only 39% of the expected total inventory found in this core.

Two different interpretations of the $^{210}Pb_{ex}$ profile are proposed. The first one leads to two similar sedimentation rates (ca. 0.25 cm yr^{-1}) for two different portions of the core, namely from 3.5 to 7.5 cm depth and from 9.5 to 16.5 cm depth. The second interpretation of the same profile, obtained by best-fitting a line between 3.5 and 16.5 cm depth, gives a sedimentation rate of 0.53 cm yr^{-1}. The fact that a similar sedimentation rate was obtained for the sediments deposited below and above the break between 7.5 and 9.5 cm depth (0.25 cm yr^{-1}) could be interpreted as a sudden and short change in the sedimentation regime. A sediment accumulation rate of 0.29 cm yr^{-1} was calculated from the position of the ^{137}Cs peak (10 cm depth-1963). According to the CRS chronology, the ^{137}Cs peak has an age between 1959 (± 34) and 1967 (± 28). Very low detectable levels of ^{137}Cs were found in pre-1950s horizons, thus excluding diffusion or mixing.

Palude della Centrega (Rosa 40)

The site is located on a tidal flat colonised by *Zostera noltii*, at the edge of a navigation channel, (the Scannello Channel), although the size of passing vessels is rather small, compared to the previous site. The sediments appear to be compact, dark in colour and consist of silts to fine silts, this latter fraction becoming dominant with depth (modal grain-size fraction of 5-6 phi, becoming 7 phi at the base of the core). As for Cona, this is indicative of a depositional environment characterised by weak hydrodynamics, favouring sedimentation of fines.

The average ^{210}Pb and ^{226}Ra activities calculated from 0 to 44 cm depth are respectively 47.32 (± 7.71) and 37.58 (± 6.76) Bq kg^{-1}. The $^{210}Pb_{ex}$ activities depth distribution exhibits totally different features compared to those of Cona and San Giacomo. The profile is very flat and no decreasing logarithmic trend with depth can be distinguished. BATTISTON *et al.* (1988) obtained a $^{210}Pb_{ex}$ similar profile in a core collected in the central basin of the lagoon concluding that it was representative of a non-depositional area. The $^{210}Pb_{ex}$ total inventory (Table 1) was calculated to be only 32% of the expected mean $^{210}Pb_{ex}$ atmospheric flux. The 137Cs total inventory calculated down to 44 cm depth exhibits a pronounced deficit with only 53% of the expected total inventory found in this core. The depth at which both $^{210}Pb_{ex}$ and ^{137}Cs are undetectable (44 cm) corresponds to an increase in water content in pair with a fining trend in grain size (Figure 2a).

From the distribution of the $^{210}Pb_{ex}$ the value calculated by least-square fit regression is between 13 and 44 cm depth gives 1.32 cm yr^{-1}, more than four times the average sedimentation rate calculated for the other two sites (Table 1). Although this may seem high, rapid sedimentation has been observed at other sites around the lagoon (FRIGNANI *et al.*, 1997; DONAZZOLO *et al.*, 1982). The CIC model would thus contradict the earlier assumption of a non-depositional site. The 137Cs inventories exhibit a large scatter (Figure 3). However, interpreting the peak of maximum 137Cs activity as the 1966 event (16.5 cm depth), this gives an average sedimentation rate of 0.47 cm yr^{-1}.

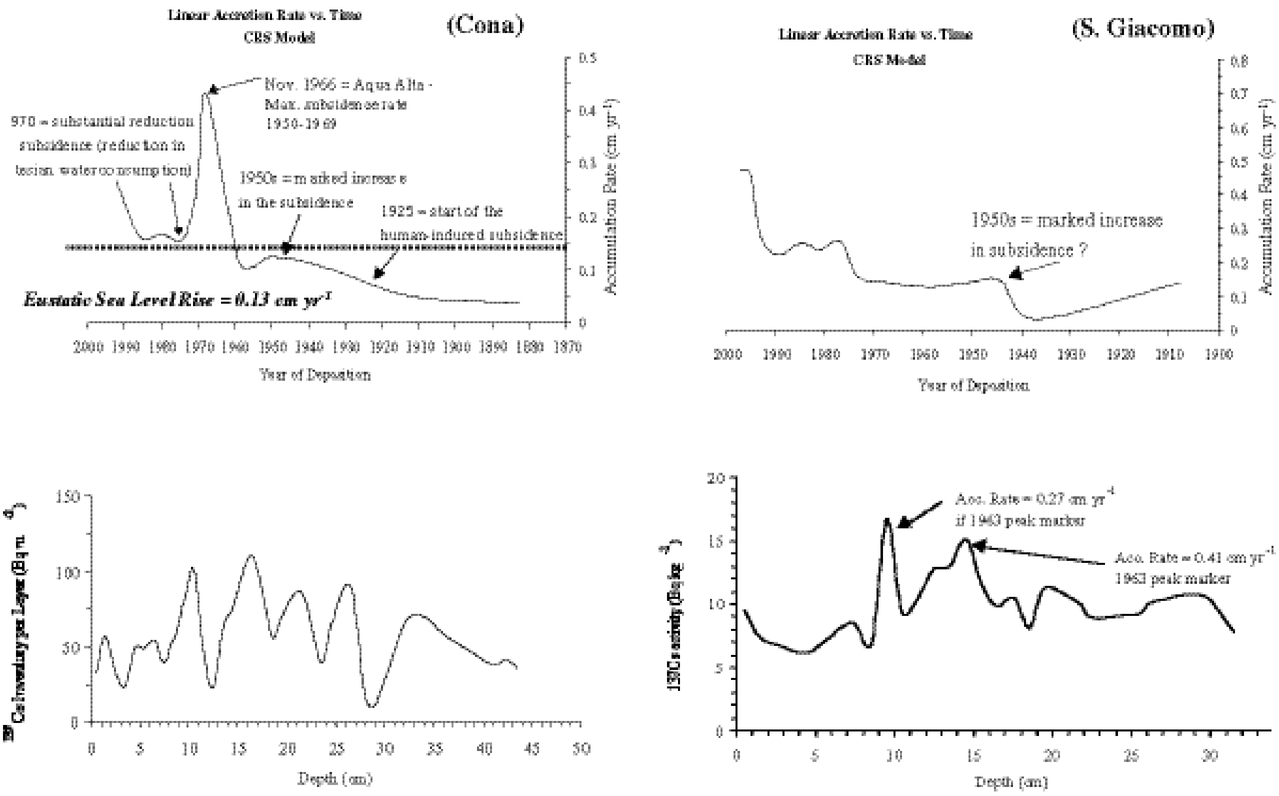

Figure 3. Most significant results of dating using radionuclides. For the Rosa and Saline cores the Cs inventories are presented to remark the problems with the interpretation.

Palude di Saline (Saline 50)

This core comes from the most sheltered site, at the edge of a creek, within a small bay protected from wave influence. The sediment composition is mud-dominated (main grain-size fraction of 5 phi), although the very fine sandy fraction (3.5-4 phi) increases between 3 and 16 cm depth, from 34% to 40%, respectively (Figure 2). A sea grass community, dominated by *Zostera noltii*, was identified at the site. Shells (fragments and/or intact) and vegetal debris were present throughout the core length, and signs of reduced horizons in the first 13 cm were observed too.

The average activities of ^{210}Pb and ^{226}Ra from 0 to 32 cm depth are respectively 43.66 (± 12.60) and 30.82 (± 5.79) Bq kg^{-1}. The $^{210}Pb_{ex}$ total inventory was calculated only for the interval 0-26 cm as the radionuclide became undetectable below this depth. This inventory is supported by an annual $^{210}Pb_{ex}$ deposition flux that represents only 52% of the mean $^{210}Pb_{ex}$ atmospheric flux over Northern Hemisphere landmasses. The ^{137}Cs total inventory could not be calculated with precision because some traces of the element were still detectable at the bottom of the core. Nevertheless, the value estimated between 0 and 32 cm, only accounts for 73% of the expected inventory.

The $^{210}Pb_{ex}$ distribution does not display a marked decreasing exponential trend. A sedimentation rate 0.98 cm yr-1 was calculated by fitting a least-square regression line between 4 and 32 cm depth and excluding two depth-intervals, for which there was no measurable $^{210}Pb_{ex}$ (12-13 and 17-18 cm depth). Like in the previous core, the ^{137}Cs record is smoothed and consequently, the 1963 peak marker broadened. However, if the deepest ^{137}Cs peak (at 14.5 cm) corresponds to the year 1963, an average sedimentation rate for the last 35 years of 0.41 cm yr^{-1} can be calculated. Using the peak closest to the sediment surface (9.5 cm), a value of 0.27 cm yr^{-1} would instead be obtained (Figure 3). Based on the ^{210}Pb chronology established with the CRS model the dates given for these two "peaks" are 1965 (± 27) and 1978 (± 19), respectively.

Relative Sea Level Rise and Acqua Alta events

A summary of the accumulation rates calculated by the CRS and CIC models, as well as the position of the 1963 peak-marker in the four cores is presented in Table 1. The best agreement between the three methods is found for San Giacomo (Site 20), with a sedimentation rate ranging from 0.22 to 0.29 cm yr^{-1}. For Cona (Site 30), both the CRS model and the position of the Cs peak-marker give the same accretion rate (0.16 and 0.18 cm yr^{-1}). Two different CIC accretion rates were calculated for this core, 0.29 cm yr^{-1} from 16.5 to 7.5 cm depth and 0.17 cm yr-1 from 4.5 to 2.5 cm depth. The patterns of accumulation can be related to recent Relative Sea-Level documented in Venice. In addition to the eustatic sea level rise of the northern Adriatic (0.13 cm yr^{-1}), human-induced subsidence began in 1925 in response to groundwater extraction and increased markedly in the early 1950s. A reduction in artesian water consumption only took place in 1970. The core shows an increase of the accumulation rate between 1910 and 1931, coincident with the start of groundwater extraction. The sediments recorded the greatest increase in accretion rate during the period between 1958 and 1973, with the maximum deposition rate (0.43 cm yr^{-1}) around 1967. Indeed, subsidence made the lagoon more susceptible to flooding during extreme high tides, caused by *Acqua Alta* (Storm Surges), like it is confirmed by historical records (Figure 4). Within the uncertainties of the method used here, Cona recorded the largest accretion rate (0.43 cm yr^{-1}) in association with the event of 4 November 1966, when the tide reached 194 cm (CANESTRELLI *et al*., 2001). The depth of the horizon related to this event (7 cm) corresponds to a break in the slope of the $^{210}Pb_{ex}$ profile. This disruption indicates that a period of steady-state accumulation was interrupted by an episode of different depositional accretion. The surge event was of extremely long duration. Historical tide data (CANESTRELLI *et al*., 2001) testify that the tide was over 110 cm high for 22 hours, with the residual of the surge being for 100 cm over 10 hours and above 50 cm for about 40 hours. A correlation between the duration of the surges and the deposition rates as corresponding to the year of occurrence was tempted, but gave non significant results.

The sedimentation rates calculated at the two other sites, Rosa and Saline, are more subject to caution (Table 1). The CRS and CIC models give values which are not significantly different (1.39 and 1.32 cm yr^{-1} for Rosa, 0.53 and 0.98 cm yr^{-1} for Saline), but when we consider the ^{137}Cs profile, some discrepancies appear, suggesting that a dispersion of ^{137}Cs may have occurred, causing penetration to pre-1950 depths. DONAZZOLO *et al*. (1982) attributed a comparable decrease and/or flattening of the ^{210}Pb activities near the surface to physical or biological mixing of the upper layers associated with anaerobic conditions. They calculated for the Palude di Cona area that bio-mixing could cause an overestimation of around 15% in accumulation rate calculations. Considering the other uncertainties associated to the method, this process was considered insignificant. Similar features (flat radionuclide profiles, presence of reduced sediments, shells and vegetal debris) were observed in the Rosa and Saline cores and could explain the Pb and Cs profiles. Finally, none of the cores has clearly recorded the Chernobyl accident.

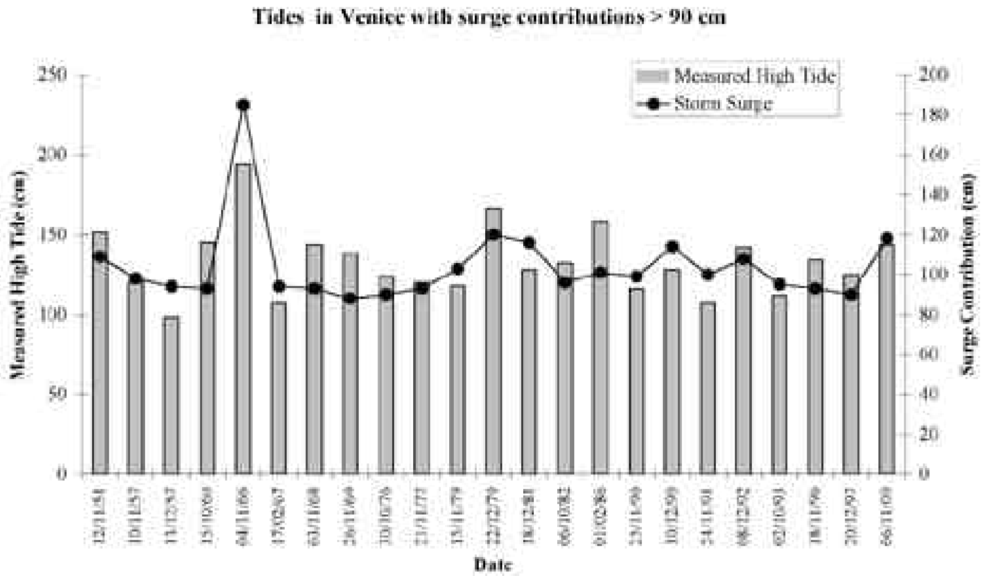

Figure 4. Historical record of storm surges in the Lagoon of Venice (after Canestrelli *et al*., 2001).

CONCLUSIONS

The site with the best agreement between the three dating methods was a mature saltmarsh that is currently suffering from lateral erosion, believed to be due navigation activities (San Giacomo-20). The sediments gave accretion rates ranging from 0.22 to 0.29 cm yr^{-1} and recorded the highest tide in the historical record (1966) as a break in the $^{210}Pb_{ex}$ profile. On the Cona (30) tidal flat, located in a sheltered area, partially influenced by freshwater inputs, both the CRS model and the position of the Cs peak-marker gave the same accretion rate, 0.16 and 0.18 cm yr^{-1}, respectively. Again, a significant break in the $^{210}Pb_{ex}$ profile was observed at a depth corresponding to the flooding of 1966. The core also recorded the effects of the lagoon's subsidence over the last century as acceleration in sedimentation rates. At the other tidal flat sites (Rosa and Saline), there is more uncertainty on the calculated sedimentation rates. Indeed, the CRS and CIC models gave results which were not significantly different, (1.39 and 1.32 cm yr^{-1}) for Rosa (tidal flat at channel's edge), 0.53 and 0.98 cm yr^{-1} for Saline (tidal flat located in a small embayment), but discrepancies appeared in the ^{137}Cs profiles.

The present study suggests the hypothesis that extreme high tides are beneficial to the sedimentary budget of upper tidal flats and saltmarshes in the lagoon of Venice. Such events may carry sediment from the lower to the upper intertidal zone and saltmarsh, generating redistribution of material. As they normally have a duration which is longer than the expected high tide, the duration of submersion allows fine sediments to settle. As some of these events are also associated to river flooding, they may coincide with periods of larger sediment input into the lagoon. Although these events may be beneficial to the sedimentary system of the lagoon, they clearly constitute an hazard for the monumental town and commercial activities, therefore they must be controlled. The Italian Government has recently (December 2001) given the "go-ahead" to the construction of flood-gates at the inlets (Mose Project), which will only enter into action with high tides over 100 cm, which currently occur approximately 7 times a year. Future research will have to address the impact of a decrease in the frequency of flooding events on upper tidal flats and saltmarshes. The present paper only concentrated on sedimentation rates in the northern basin and spatial variability is expected across the lagoon, also in view of the different continental input of the three lagoon's compartments.

ACKNOWLEDGEMENTS

The field work was supported by the EU F-ECTS Project (Contract No. MAS3-CT97-0145), while radionuclide dating was supported by the EU TMR-SWAMIEE Project (Contract No. ERBFMRX-CT97-0111). The first author acknowledges partial financial support from the University of Ferrara (ex-60% funds, year 2001) and the help of Ms C. Evarchi in the field and in the laboratory.

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